

PL-TR-95-2023

**DESIGN, EVALUATION, AND
CONSTRUCTION OF TEXESS AND
LUXESS, AND RESEARCH IN MINI-ARRAY
TECHNOLOGY AND USE OF DATA
FROM SINGLE STATIONS AND SPARSE
NETWORKS:
PHASE III**

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October 1994

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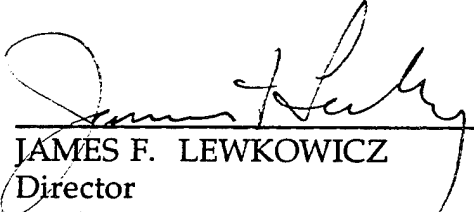
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13. ABSTRACT (Maximum 200 words) Objectives are : (1) conduct research in seismic mini-array technology and single stations and sparse networks data, (CLIN 1) and (2) design, evaluate, and construct TEXESS, in Southwest Texas, and LUXESS, northeast of Luxor, Egypt, (CLIN 2), along the lines of a GSE Alpha Station. TEXESS was installed by SMU personnel in August 1993, and the first event was a local recorded on 31 August. With de-installation on hold awaiting diplomatic agreements, work has been directed to CLIN 1 research. Research on time-domain processing of array data has resulted in a significant decrease in the standard deviation of azimuths as compared with <i>f-k</i> processing. For example, a reduction of azimuthal standard deviations from ± 15 degrees with <i>f-k</i> processing to ± 1.4 degrees with time-domain processing. The Ms:mb method is an effective and transportable discriminant for shallow events at teleseismic distances with <i>mb</i> greater than 4.75. SMU has been successful in reducing the detection threshold for fundamental mode Rayleigh waves using signals at regional distances for body wave magnitudes as low as 3. Autoregressive (AR) modeling on <i>Lg</i> data has resulted in the ability to discriminate small economic explosions from small earthquakes.				
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SUMMARY

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Objectives

Objectives of the contract are twofold: (1) to conduct research in seismic mini-array technology and use of data from single stations and sparse networks, and (2) to design, evaluate, and construct two mini-arrays, TEXESS (Texas Experimental Seismic System) in Southwest Texas and LUXESS (Luxor Experimental Seismic System), which is northeast of Luxor, Egypt. These two tasks are dubbed CLIN 1 and CLIN 2.

The original CLIN 1 objectives were to: (1) conduct research in the use of single station and sparse network data in detecting and identifying small seismic events, (2) conduct research to develop optimum configurations and processing techniques for a nine-element mini-array, and (3) to continue development of an unmanned intelligent seismic station. These objectives have been revised by the Project Office in April 1994 as described on page 4 under Implications for Further Research.

CLIN 2 objectives are to: (1) acquire hardware and software, (2) install TEXESS, (3) perform site surveys and choose location for LUXESS, (4) test TEXESS and perform verification tests prior to de-installation, (5) de-install TEXESS, (6) complete civil work in Egypt, (7) install and test LUXESS, (8) de-install data acquisition, analysis and archiving equipment and ship to Helwan, Egypt, data center, and (9) install and test data acquisition, analysis and archiving equipment at Helwan data center.

Technical Problem

The German Experimental Seismic System was dedicated in 1992 and represents an upgrade for regional arrays. Although GERESS was technologically advanced over NORESS and ARCESS, which were earlier regional arrays, because of greater sensitivity and wider dynamic range, there was a considerable effort that resulted in increased costs for pier and vault construction and trenching for power cabling. Now, in TEXESS, innovations in emplacement techniques, such as the installation of sensors in shallow boreholes instead of vaults and the use of solar power at each site to eliminate cabling from a central-power source, that have reduced array-installation costs by an order of magnitude. Other innovations are discussed below. TEXESS is, therefore, a proposed design for a GSE-Alpha station because of these cost-cutting innovations. In addition to design, construction, installation, and operation, of TEXESS, research will be undertaken to develop new means of taking data and handling the data.

General Methodology

In GSE/US/84, February 1993, entitled "Technical Concepts for an International Data Exchange System," the GSE established the design goals of a future system. Goals are as follows:

1. Provide prompt access to all essential data
2. Provide convenient access to all available data
3. Provide direct access to all data at authorized national and global facilities
4. Accomplish goals with realistic manpower and budget resources.

The new concept of a global system for data exchange calls for an Alpha Network of 40-60 stations, primarily arrays; plus much greater than 60 Regional or Beta Stations; plus Local and National Networks or Gamma Stations.

SMU began research on mini-array technology in 1991 on a previous contract. The proposed design was along the lines of an Alpha Station consisting of an array containing nine sites. Advancements over the GERESS design included the following:

1. The placement of seismometers and electronics in boreholes to greatly reduce construction costs for piers and vaults
2. The use solar power at each site rather than a central-power source
3. The use GPS receivers for time data at each seismometer site to replace central timing from the Hub
4. The employment of radio links from seismometer sites to the Hub to replace cable links and associated construction costs
5. The use of modular equipment to facilitate the installation and maintenance of the array.

Four shallow boreholes about 7 meters deep and 11-5/8 in. in diameter were drilled and cased with standard 8-in. pipe. Special equipment and techniques were developed to lower and level seismometers in the boreholes. A prototype solar power array and directional antenna were also developed for installation at LTX.

Technical Results

The limited program described above was successful and SMU was granted a contract to design, evaluate, and construct two nine element experimental mini-arrays: TEXESS and LUXESS.

Important Findings and Conclusions

The SMU mini-array research program that was begun in 1991 under the previous contract proved the feasibility of the proposed design and methodology described above.

Significant Hardware Development

Preliminary research has led to the following hardware developments:

1. The development of seismometer emplacement techniques in boreholes, including remote seismometer locking eliminated the need for vaults
2. Advancements in computer applications and radio modems allow all necessary electronic components to fit inside a 8-in. casing to provide physical protection and a more stable environment for the electronics
3. The use of Global Positioning Satellite (GPS) receivers to obtain timing accurate to within 10 ms of world time assuring time synchronization of the array
4. The use of modern digital radio modems allows the system to perform as a local area network referred to as a RAN (Radio Area Network); radio polling software provides wide bandwidth intra-array communications while requiring two base-station radios; the need for expensive buried fiber-optic cable is eliminated
5. A NEMA enclosure is mounted on top of the borehole and is used to house the batteries and as a mount for the solar-power array; the GPS receiver and radio antenna are mounted above it.

Special Comments

The task of adapting the solar-panel arrays at Lajitas to the LUXOR environment is simplified somewhat in that both TEXESS and LUXESS are at approximately the same latitude, 30 deg North; both are in arid climatic zones; and both have about 3,500 annual hours of sunshine. As a result, there would be no need to modify the prototypic TEXESS design because of differing environmental conditions at LUXESS.

Implications for Further Research

CLIN 1 objectives were revised by the Project Office in April 1994 to: (1) conduct research to develop optimum configurations and processing techniques for nine- and sixteen-element short-period arrays, (2) conduct research in discrimination of nuclear events using autoregressive (AR) modeling techniques on Lg data, and (3) conduct research in measuring 20-

second Rayleigh waves at regional distances using high-resolution, wide-dynamic-range, short-period, seismic-array data and broadband KS 36000 data. Appendix A of this report is by Eugene Herrin entitled "Dealing With Outliers and Possible Evasion Scenarios." And Appendix B is by Eugene Herrin, Paul Golden, and J. Theodore Cherry entitled "The ARPA Model 94 Regional Array Concept."

CLIN 1 -- RESEARCH

Array Research

Conduct research to develop optimum configurations and processing techniques for nine-and-sixteen element short-period arrays,

In Scientific Report No. 1, PL-TR-94-2106, we discussed the problems of the large scatter of the order of ± 15 deg of azimuth estimates at GERESS after $f-k$ processing. In order to address this problem, SMU research has concentrated on developing a time-domain processing techniques to reduce this statistic using the nine-element TEXESS array. The array-processing technique is similar to that described by Bernard Massinon in his paper entitled "The French seismic network -- current status and future prospects," which he presented at the GERESS Dedication and Symposium on 24 June 1992. The processing algorithm developed by SMU using GERESS D-ring data, which approximates the proposed 9-element TEXESS array, was presented in SMU-R-92-396, p. 14-17.

In Scientific Report No. 2, PL-TR-94-2258, array-processing research is described in Appendix 1. Specifically, Appendix 1 describes work on time-domain processing of GERESS and TEXESS data to decrease azimuthal-error statistics with respect to that obtained by $f-k$ processing. Time-domain processing has resulted in a reduction of azimuthal standard deviations from ± 15 degrees with $f-k$ processing to ± 1.4 degrees with time-domain processing of TEXESS data. The plan is to integrate the time-domain process with a detector that is being designed by Chris Hayward in order to automate array processing.

Discrimination Research

Conduct research in discrimination of nuclear events using autoregressive (AR) modeling techniques on Lg data

In the framework of a Comprehensive Test Ban Treaty (CTBT), discrimination between low-yield or decoupled nuclear explosions, economic explosions and small shallow earthquakes using the characteristics of the seismic waves becomes very important. Some of the economic explosions are multiple-source events with a time and space pattern dependent upon the type of application. The superposition of the seismic motion in the time domain leads to regular amplification and suppression of spectral power in the frequency domain. As, in general, single events (single explosions or earthquakes) do not exhibit spectral modulations, their presence can be used in the discrimination between single and multiple events. The aim of the present study is to develop a fast and robust method of discriminating between earthquakes and economic explosions based on differences observed in the spectral content of the regional waveforms. The method is based on the parametric estimation of the power-spectral density (PSD) using the autoregressive (AR) Burg algorithm of order 3, which provides a fast method to emphasize the spectral differences.

In Scientific Report No. 2, AR modeling is described in Appendices 2 and 4. The initial data set (see Table 1) includes about 30 mine explosions and earthquakes from the Vogtland area of Czechoslovakia about 200 km northwest of GERESS. The frequency and reciprocal pole position of the complex pole in the AR (3) models were calculated using the Lg arrival for the Vogtland events recorded at GERESS in Table 1. Figure 1 shows a clear separation of explosions and earthquakes with the latter having broad spectra with "weak" poles above 6 Hz whereas the explosions all show much "stronger" poles at frequencies less than 5 Hz. The AR (3) method appears to be an effective discriminant for small explosions and small earthquakes. Further work will be to answer questions regarding the method: (1) its effectiveness in other areas such as the Middle East, (2) its effectiveness using larger events, and (3) why the method works as well as it does?

Event #	Date	Lat(N)	Long(E)	Depth	M	Yield(kg)	Origin time	Eq/Qb
1	3/11/91	50.207	12.685	0	1.98	3,265	12:03:23.986	qb
2	3/21/91	50.207	12.685	0	2.05	3,982	12:04:14.701	qb
3	3/22/91	50.207	12.685	0	2.03	2,835	12:33:25.332	qb
4	3/23/91	50.207	12.685	0	1.99	2,025	12:00:55.800	qb
5	3/24/91	50.296	12.225	12.9	2.18		05:05:04.447	eq
6	3/24/91	50.279	12.228	12.9	1.5		05:35:21.047	eq
7	3/24/91	50.277	12.24	13.9	1.4		06:57:59.309	eq
8	3/24/91	50.278	12.22	12.4	1.65		09:38:33.436	eq
9	3/24/91	50.294	12.223	12.7	2.07		14:33:27.988	eq
10	3/24/91	50.293	12.224	12.5	1.8		15:00:44.532	eq
11	3/24/91	50.293	12.224	9	1.73		15:41:03.515	eq
12	3/25/91	50.298	12.222	12.9	2.37		14:54:13.507	eq
13	3/25/91	50.292	12.213	12.4	1.54		22:31:45.761	eq
15	5/2/91	50.207	12.713	0	1.93	3,575	11:06:10.221	qb
16	5/2/91	50.184	12.186	0	2.03		12:47:33.067	qb
18	5/10/91	50.79	12.07	-999	1.43		20:02:51.112	eq
19	5/19/91	50.36	12.371	0	2.06		03:22:10.0	eq
20	5/23/91	50.207	12.713	0	2.12	3,135	11:01:05.259	qb
21	5/25/91	50.207	12.713	0	2.13	3,135	11:01:28.688	qb
22	5/26/91	50.207	12.713	0	2.14	2,907	11:00:32.367	qb
23	5/28/91	50.207	12.685	0	2.01	3,575	11:03:51.425	qb
24	6/20/91	50.207	12.685	0	1.98	1,998	11:01:16.808	qb
25	6/20/91	50.293	12.803	0	1.8		11:45:35.486	qb
26	6/22/91	50.207	12.685	0	2.15	2,886	10:58:34.818	qb
27	6/27/91	50.207	12.685	0	1.93	3,515	11:04:39.629	qb

Table 1. -- Earthquakes and Explosions from Vogtland Area.

Conduct $M_S:m_b$ research by measuring 20-second Rayleigh waves at regional distances using high-resolution, wide-dynamic-range, short-period, seismic-array data and broadband KS 54000 data.

The $M_S:m_b$ discriminant has been investigated by a number of researchers for both regional and teleseismic events and explosions. Bases for the discriminant are (1) that explosions emit more energy in the form of high-frequency body waves and (2) that earthquakes emit more energy in surface waves having low frequency radiation; therefore, an $M_S:m_b$ plot displays a significant separation of the two populations. The problem with the method is that of identifying small explosions; that is, the problem boils down to seismograph sensitivity. With the installation of new high-dynamic-range seismographs at TEXESS, planned research includes the determination of M_S from small earthquakes at regional distances using the TEXESS array data recorded by short-period GS-13 seismometers and a posthole, broadband KS 54000 seismometer. In Scientific Report No. 2, $M_S:m_b$ studies are described in Appendices 3 and 4, and are excerpted here.

The $M_S:m_b$ method was shown to be an effective and transportable discriminant for shallow events at teleseismic distances with m_b greater than 4.75. Further research was carried out including the construction of long-period arrays in an attempt to lower this threshold, but until recently, essentially all data was obtained from stations at teleseismic distances.

Now the construction of regional arrays for monitoring a proposed CTBT has led to considerable interest in reducing the detection threshold for fundamental mode Rayleigh waves using regional signals. The goal of our proposed studies is to identify shallow earthquakes at regional distances with magnitude (m_b) as low as 3.0 using the $M_S:m_b$ method.

The GERESS regional array in eastern Bavaria provided the first high-resolution array data with linear dynamic range greater than 120 dB. Although in 1992 there was no broadband sensor at GERESS which could resolve long-period noise at a 20 sec. period, it was possible to use the short-period sensors for this purpose. The GS-13 sensors at GERESS have their resolution at 0.05 Hz (20 sec. period) limited by self-noise which is about 20 dB

above the Low Noise Model (Peterson, 1993, and Rodgers, 1992). The random nature of this self-noise and the small aperture of the array relative to the wavelength of 20 sec. Rayleigh waves make it possible to improve the signal-to-noise ratio by about 14 dB simply by summing the output of the 25 short-period sensors. The 120 dB resolution then allows the sum to be low-pass filtered (corner at 0.1 Hz) in order to observe long-period signals. This method has been used to resolve the ambient seismic background noise at GERESS at periods of 10 to 20 seconds.

The prototype ARPA Model 94 regional array at Lajitas (TEXESS) has nine vertical GS-13 (SP) elements and a posthole KS54000 broadband (BB) system. The SP and BB data are recorded with linear dynamic range greater than 120 dB, with the SP's using SHI AIM 24 ADC's and the BB's using an RDAS 200 ADC. The KS54000 at TEXESS is sand-packed in a 7-m-deep borehole resulting in a total installed cost less than half that of the standard KS36000 in a 100 m deep borehole. An AFTAC standard KS36000 system is collocated with the KS54000, but the data from that instrument are recorded with a linear dynamic range of about 70 to 80 dB.

The sum of the GS-13 elements at TEXESS results in a self-noise threshold about 10 dB above the Low Noise Model at a period of 20 sec. The KS54000 should be capable of resolving the Low Noise level at 20 sec. We have used both the SP array sum and the posthole BB vertical to look for 20 sec. Rayleigh waves in regional signals.

Aftershocks from the Northridge earthquake, a distance just over 1500 km from Lajitas, were used to prepare a database for which location, origin time, local magnitude and, in some cases, m_b were known from USGS reports (See Table 1, Appendix 3, Scientific Report No. 2, PL-TR-94-2258 for Northridge-aftershock data base). One aftershock on 19 January 1994 (m_b 5.0) was selected as a reference event. First, the SP array was beamed at the event using a cross-correlation method to determine back azimuth, horizontal phase velocity and static corrections for the Pn arrival (az. 291°, vel. 8.46 km/sec.). Figure 2 shows that the residuals for this fit for all possible cross-correlations between elements are all less than one sample point (0.025 sec. for 40 sps data). The set

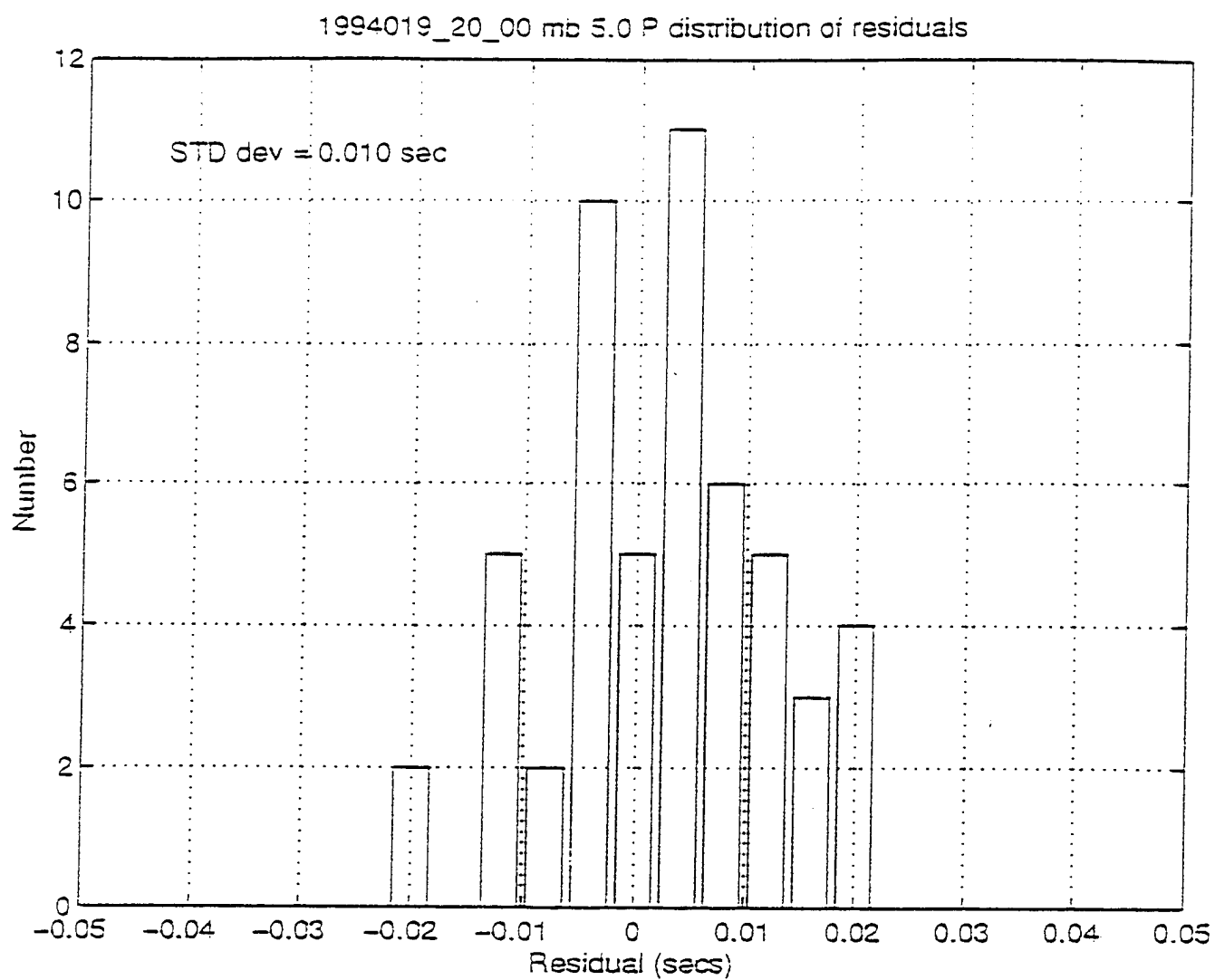


Figure 2. -- Histogram of residuals from Northridge aftershock.

of delays from this fit was used to form beams for 24 smaller aftershocks. These array sums were then used to compute m_b (Pn) for Lajitas.

Both the sum of the SP channels and the vertical BB (post-hole) channel were Butterworth, low-pass filtered at 0.10 Hz with three poles forward and three reversed in order to eliminate any phase shift. The filtered wave forms for the SP sum and BB Z were essentially identical. Figure 3 shows the results of a multiple filter analysis of the reference event using a program supplied by R. Herrmann. The indicated Rayleigh wave dispersion curve was used to design an optimum phase-matched filter (Herrin and Goforth, 1977) which when applied to the reference event produced the results shown in Figure 3. This filter, adjusted for slight differences in epicentral distance, was applied to the low-pass filtered SP sum for 24 events and the low-pass filtered BB Z for 6 events. Spectral M_s at 0.05 Hz was then calculated from the Pseudo Autocorrelation Function (PAF) produced by the phase-matched filters using the formula

$$M_s = \log A/T + \log \Delta \quad (1)$$

where A is the spectral amplitude and Δ is the epicentral distance in degrees.

Table 1 shows the m_b (Pn) and M_s values for the 25 events which are ordered in decreasing values of ML. It was observed that, on the average, m_b was about 0.3 magnitude units smaller than ML so that the range of magnitudes for the data base was from about m_b 2.7 to 5.0.

M_s values from the SP sum and the BB Z were essentially the same. For both data sources the 20 sec. Rayleigh wave was lost in the noise for events with M_s less than about 3.0 (m_b about 3.5). From Table 1 it is clear that M_s is decreasing faster than m_b with decreasing event size. We can speculate that the value of M_s (20 sec.) for a m_b 3.0 Northridge aftershock would be about 2.5, but neither the SP sum or the BB Z were able to resolve 20 sec. Rayleigh waves at this level. The 1500 km path from Northridge to Lajitas crosses the Coast Ranges, the Basin and Range Province, and the southward extension of the Rio Grande Rift. This path, roughly analogous to paths across

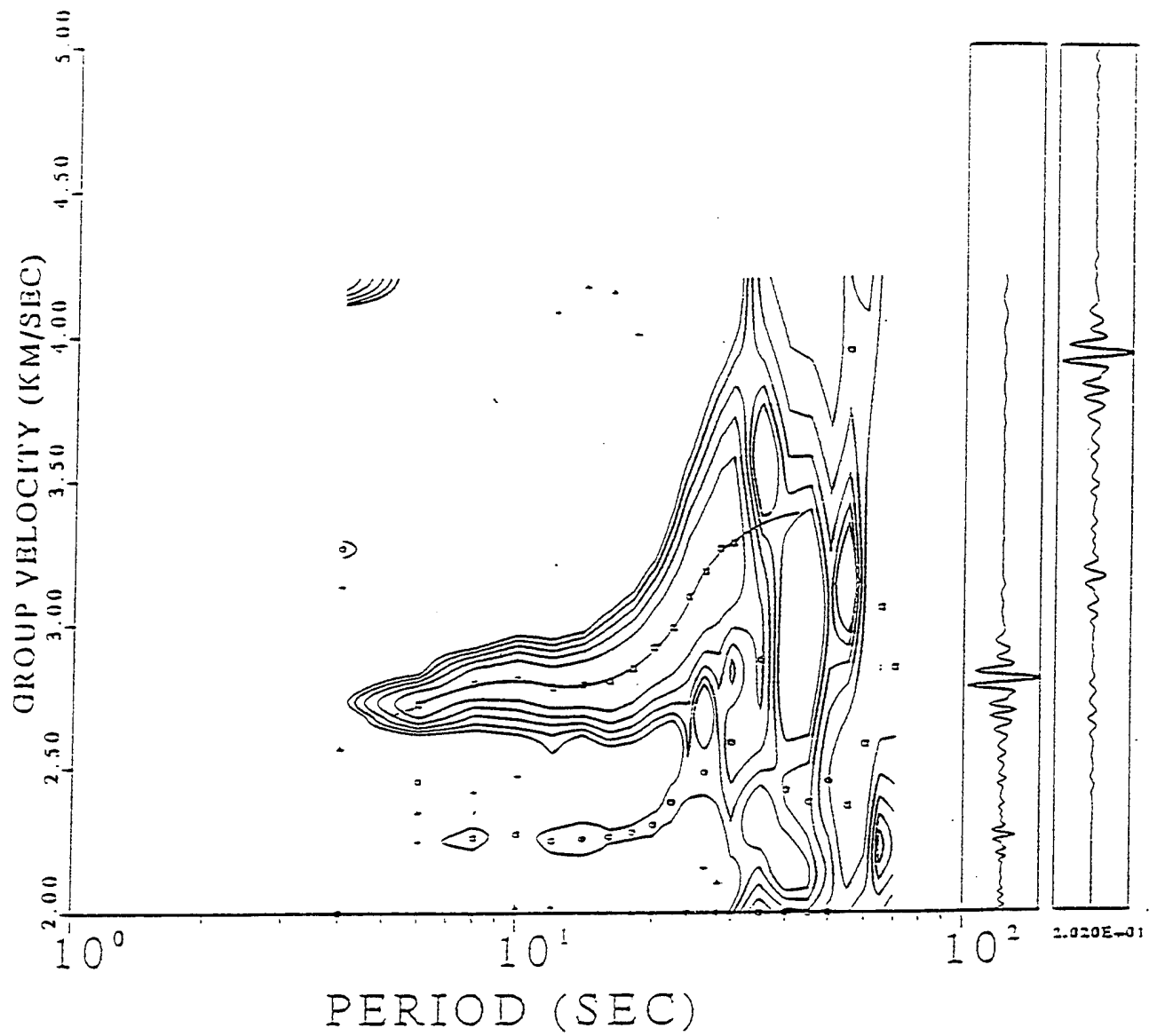


Figure 3. -- Rayleigh wave group dispersion curve for Northridge aftershock.

tectonically active areas in the Middle East, causes considerable attenuation of Pn and Rayleigh waves. Thus the use of the Northridge - Lajitas data set to test the $M_s:m_b$ technique at regional distances constitutes a kind of "worst-case" test of the method.

If we are to lower the M_s measurement threshold for this data set to m_b 3.0, we must investigate the nature of the noise floor which now limits the resolution. The SP sum at 20 sec must have a noise floor at or greater than the instrument noise (10 dB above the Low Noise Model) and the BB Z must have a noise floor set by the ambient 20 sec noise at Lajitas (near the Low Noise level) or by non-linear effects caused by the large output voltages at higher frequencies. But the SP sum and BB Z were recorded on different systems and both systems exhibited the same noise floor well above the predicted limits; that is, essentially equivalent to the spectral amplitudes for M_s 3.0 events.

What is the nature of the 20-sec. "noise" which limits the M_s measurements at Lajitas for the Northridge events? How is the "noise" related to ambient background in the absence of regional signals? Can methods be found for increasing the signal-to-"noise" ratio by about 10 dB in order to obtain M_s measurements for m_b 3.0 events in Southern California?

For Northridge events of m_b about 3.5 the M_s (20 sec.) value has decreased to about 3.0. The use of phase-matched filtering has removed the dispersion effects so that spectral amplitude measurements at or near an Airy phase can be made reliably. Quoting from Davies (1968, SIPRI, p. 62) "When magnitude determination at 20 seconds proves impossible at near distances, Thirlaway considers 12 sec. period waves and applies an appropriate correction...." Would a choice of 12 or 15 sec. period for the M_s measurement result in a significantly lower threshold?

CLIN 2 -- DESIGN, EVALUATION, AND CONSTRUCTION OF TEXESS AND LUXESS

Experimental-Array Program

Information on the experimental-array program at SMU on the previous contract was presented in SMU-R-92-396 and in Scientific Report No. 1, PL-TR-94-2106.

TEXESS AND LUXESS

Acquisition of Hardware and Software

The First and Second Quarterly R & D Status Reports cover the acquisition of hardware and software. TEXESS and LUXESS equipment are discussed in Scientific Report No. 1, PL-TR-94-2106. Instructions for the installation of the Posthole 54000 seismometer are presented in Appendix 5 of Scientific Report No. 2.

Array Hardware

Hardware is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Computer Hardware

Computer equipment is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Software

Acquisition of software was addressed in Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Install TEXESS

Layout

TEXESS layout is discussed in Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Installation

Installation is discussed in the Scientific Report No. 1, PL-TR-94-2106, ADA284580.

Perform Site Surveys and Choose Locations for LUXESS

SMU has received communications from the National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Egypt, requesting a draft Memorandum of Understanding (MOU). Arrangements are presently being pursued by respective State Departments.

Two locations have been identified for LUXESS. Both are on granitic bodies located north of the road between Luxor and Quseir. Preliminary siting was done by SMU personnel using enhanced digital imaging of photos from the French SPOT satellite and the Russian DD5 satellite. DD5 images have a pixel resolution of less than 3 meters, which makes jeep trails, individual houses, and access routes clearly visible. Figure 4 is a digitally-enhanced Landsat image of the two circular granitic intrusions. The upper right corner of the photo shows the coastline of the Red Sea near the village of Quseir.

Test TEXESS Prior To De-installation

System fidelity tests were conducted by Chris Hayward and Dick Kromer during the week of 14 November 1993. During this period, engineering refinements were made by Karl Thomason.

A probable lightning strike in October 1994 resulted in a decision to reconfigure the radio system at the hub. The original configuration shown in



Figure 4. -- Digitally-enhanced Landsat image of eastern desert of Egypt showing granitic intrusions west of Quseir.

Figure 2 of Scientific Report No.1, PL-TR-94-2106 consisted of two radios: one that transmits (polls) and receives and a second that receives only. The former went out causing the array to go down. It was found that the stroke destroyed the bridge rectifier in the power-supply circuitry, and it was sent to the manufacturer, REPCO, for repair.

Because we were unable to make a portion of the array operational by reconfiguring the receive radio to transmit, we decided to make the hub fully redundant. As a result, there will be two spare radios, a spare CIM, and additional lightning-protection equipment. This second hub system will be cabled and configured identical to the operating system and act as a standby system in case of another radio failure. Our local representative will be trained to do electronic maintenance and to disconnect the original system from the antenna and UPS and plug in the standby system in case of another failure.

De-install TEXESS

During the early part of the week of 21 November 1993, SMU principals made an inspection trip to TEXESS in order to make plans for de-installation, packing, and international shipment.

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APPENDIX A. -- DEALING WITH OUTLIERS AND POSSIBLE EVASION SCENARIOS

Eugene Herrin

INTRODUCTION

The primary network for testing monitoring capability in GSETT-3 should detect more than 100,000 events per year with magnitude 2.5 or greater. If a single, clandestine, underground nuclear explosion with a yield of a few kilotons, possibly decoupled, were to occur during the first decade under a CTBT, the International Seismic Monitoring System (ISMS) would face the formidable task of providing data that would identify one event in a million as a nuclear test. The ultimate responsibility for making such an identification will reside with the various National Analysis Centers using all information available from both the ISMS bulletin and National Technical Means (NTM). This identification process will be one of eliminating events from consideration based upon all available discriminants including location and magnitude. The remaining events, which we call "outliers" in that they cannot, with high confidence, be classified as non-nuclear must be carefully considered. Too many outliers can overwhelm the process.

The possibility of evasion further complicates discrimination analysis in that clandestine tests may be masked by explosions, rock bursts or earthquakes that would normally be detected and located, but then excluded from further consideration. A National Analysis Center must answer the following questions:

Can the number of outlier events be reduced to a manageable level?

Is there a high probability that a clandestine event, assuming various evasion scenarios, would be among the outliers?

OUTLIERS

During GSETT-2 over 900 regional events were observed by the three-component station at Lajitas and reported to the IDC's during a six week period. Because we have no reason to believe that the seismic activity in the region was unusual during that period, we predict that the prototype ARPA Model 94 regional array at Lajitas will record more than 8000 regional events per year. If an automated discrimination system were in place that had a classification probability of 0.99, then the system would be expected to produce about 80 unclassified or outlier events per year from this one GSE array located in a region of low seismicity.

Supposing that a National Analysis Center were able, using all available discrimination criteria including NTM and political considerations, to develop a system with a remarkable classification probability approaching 0.999, we might expect more than 100 outlier events per year from a network consisting of 50 GSE arrays. Even this system would be inadequate. For political reasons, a national center would need to narrow consideration to a few suspect events each year in areas of interest.

The events that must be considered consist of natural earthquakes and aftershock sequences, earthquake swarms, rock bursts and tremors induced by underground mining, shallow earthquakes induced by hydrocarbon production, industrial explosions and, of course, nuclear tests. The purpose of a discrimination system is to eliminate from consideration all but the last category of events. The previous paper has discussed promising discriminants and a methodology for combining them using an outlier-detection approach. The outlier problem would be readily solvable if it were not for the possibility of evasion. A tamped nuclear explosion of 1 kiloton can be expected to produce an event of about magnitude 4, therefore, the discrimination system could eliminate all events smaller than magnitude 3.5, and the number of outliers would be reduced to a manageable number. The possibility of evasion, the subject of the next section of this paper, is the threat that drives up the number of outliers.

EVASION

A state may choose to test a nuclear device without any attempt to avoid detection as did India 20 years ago. One purpose of such a test might be to apprise the world of its new status as a nuclear power. Under a CTBT, however, there might well be severe political and military repercussions from such a demonstration. A developing nuclear power, under these conditions, might consider testing only when further technological development required a test. They would probably plan the test in such a way as to avoid detection or attribution. A low-yield test near the sea-air interface in a remote ocean might be detected, but attribution could be very difficult. In this paper, however, we are concerned with attempts to avoid detection and identification by the seismic monitoring system. In my opinion, there would be little incentive for a state to test a "Trinity" device. Such a device is almost sure to work, is large and difficult to deliver, and is wasteful in its use of plutonium. A boosted implosion device with a yield of a few kilotons would be a much more practical weapon. Though the design of such a device cannot be discussed in this forum, it should be possible for developing nuclear power to obtain the required technology and materials. There would be, however, considerable uncertainty regarding the performance of such a device - would it go nuclear and, if so, at what yield? Before a state would commit to the manufacture of nuclear devices of advanced design for its own military use or for sale to another country, one or more successful tests would probably be required.

A prudent worldwide monitoring strategy requires a detection threshold not at 10 to 15 kilotons, but at 1 to 2 kilotons and a consideration that tests of this size could be carried out in such a way as to avoid detection as a nuclear explosion. The most effective means to evade the system would involve testing such a device in a cavity with a radius of 25 to 30 m. An industrial explosion could be used to mask the decoupled nuclear test.

For full decoupling the minimum cavity radius is

$$R = 25 Y^{1/3} \text{ meters}$$

where Y is yield in kilotons.

Assuming a decoupling factor of 70, a 1 kt. explosion in a cavity with a radius of 25 m should produce a seismic signal appropriate for a tamped nuclear explosion of 14 tons or a tamped HE explosion of about 7 tons. The magnitude of the event would be about 2.5.

Going back to the early literature on this subject (Latter et al. 1959) the corner frequency of the seismic source for full decoupling is

$$\omega_0 = \frac{c}{R}$$

For salt with $c = 4000$ m/sec, for 1 kt decoupled,
 $f_0 = 25$ Hz.

From Latter et al. (1959) the corner frequency of a tamped nuclear explosion (extrapolating from Rainier data) is

$$\omega_0 = 25 \left(\frac{1.7}{Y} \right)^{1/3}$$

For 14 tons nuclear or 7 tons HE,
 $f_0 = 20$ Hz.

More recent studies have refined these estimates of corner frequencies, but do not contradict the following conclusions. The spectra of seismic signals from a decoupled, low-yield nuclear explosion is very similar to spectra of signals from an HE explosion with the same magnitude and for the above case, the spectral corners are at frequencies too high to be observed by the ISMS. The monitoring system is faced with finding that one event in a million that could be a 1 kt nuclear test or a 7 ton HE underground explosion.

It is also possible for the decoupled test to be masked by a surface explosion. Such industrial explosions are common in many countries. In the United States, according to Paul Richards (Lamont - Doherty Earth Observatory Contribution No. 5219), there are hundreds of surface explosions per week with local magnitudes greater than 2.5, but probably no more than 30 per year with teleseismic m_b greater than 3. An m_b of 3 or greater would be required to mask a 1 kt decoupled explosion.

Data on explosions in two coal fields in the Eastern Transvaal of South Africa have been reported in GSE/RSA/7. They show that the Ermelo field produced 134 events in 4 months and the Evander field produced 59 events in the same

time period with local magnitudes from 2.0 to 3.8. Extrapolating, we would expect the following number of events per year from the coal fields:

Over 700 per year 2.0 or larger
About 440 per year 2.5 or larger
About 130 per year 3.0 or larger
A few per year 3.5 or larger.

It must be emphasized that these are local magnitudes. A limited number of calibrations show that local magnitudes tend to be larger than m_b for the same events by 0.3 to 0.5 units. We will not pursue this calibration problem in this paper, but it is very important to the construction of a meaningful event bulletin by the IDC.

Although the many small industrial explosions worldwide will create an enormous processing load for the IDC during GSETT-3, the number of the explosions larger than m_b 3.0 that might be used to mask a decoupled test may be only a hundred or so a year. Treaty protocols can be written that require preannouncement of industrial explosions above a certain size so that special monitoring steps can be taken to insure that the explosions do not mask a clandestine test. There are two other classes of events associated with industrial operations that can only be predicted in a statistical sense, namely, mining-induced rock bursts and tremors and shallow earthquakes induced by hydrocarbon production. In this paper, I will concentrate on the latter; however, the analysis used to describe induced activity in oil fields has been successfully used to describe mining-induced seismic activity in deep gold mines in South Africa.

Figure A1 illustrates induced seismic activity from the Lacq gas field in Southern France over a 14 year period. These shallow earthquakes result from subsidence as the fluid pressure in the producing horizon is reduced by gas production. Gas fields with similar induced activity have been found in the former Soviet Union and the Middle East. In particular, the War Wink gas field in the Permian Basin of Texas has been studied in sufficient detail to provide the data required for a careful analysis of the induced activity (Keller et al., 1981 and Doser et al., 1991). The data consisted of a listing of

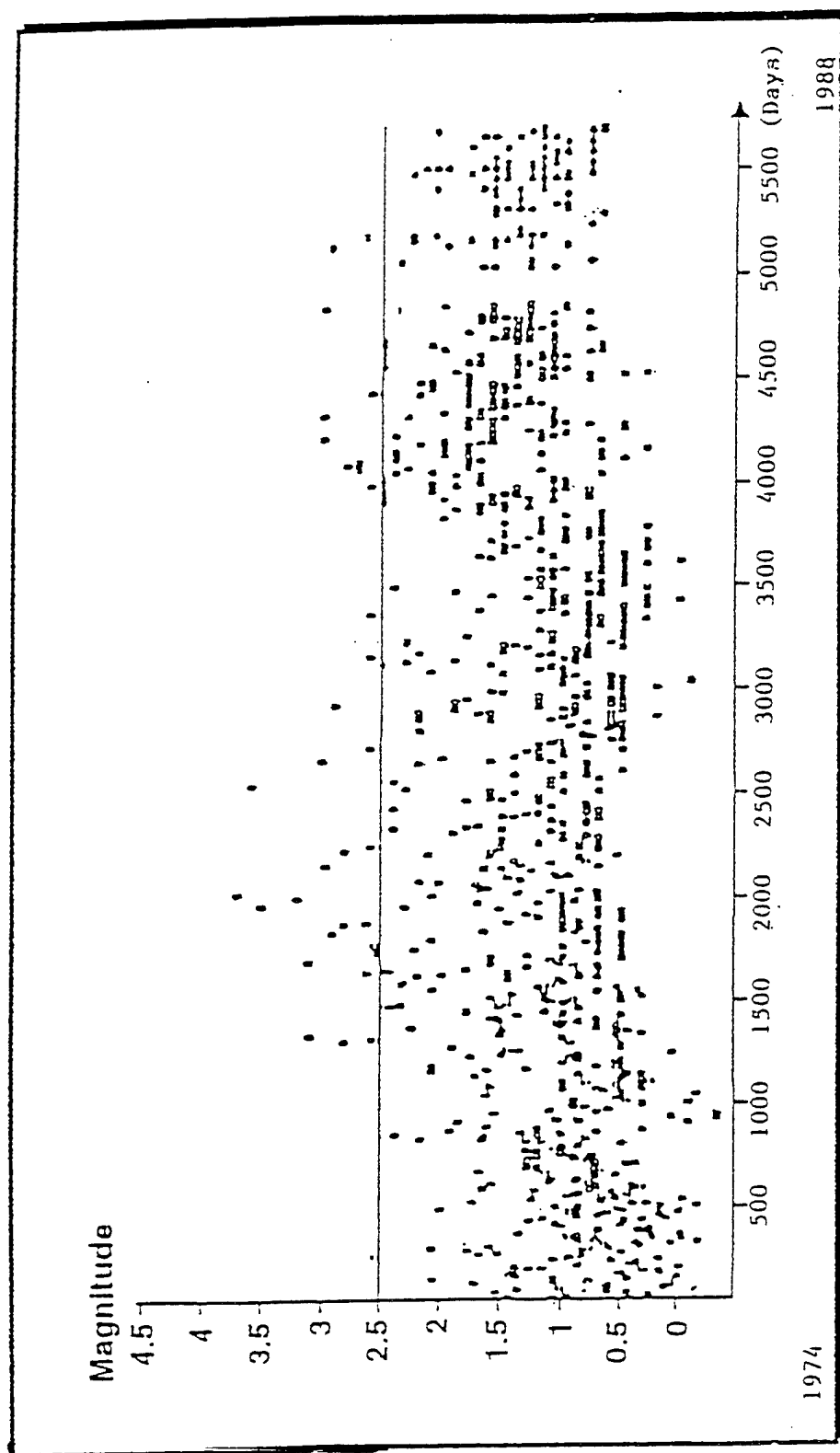


Figure A1. -- Magnitude of seismic events induced by gas production from the Lacq field in southern France.
Modified from Maury, et al., 1990.

magnitudes, which had been calibrated to teleseismic m_b for the region, for induced earthquakes at War Wink over a period of nearly four years. A histogram of magnitude vs. number of events was constructed that yielded the points in Figure A2. From this incremental distribution a b-factor was determined. The analytical model to be used assumes that, because the geometry of the gas field is fixed, there will be a fixed upper limit for the magnitude of induced events. Furthermore, following Kagan and Knopoff (1978), we assume that earthquakes smaller than the maximum event constitute a fractal process. This process can be represented by a continuous distribution as follows:

FREQUENCY:

$$f = \begin{cases} \frac{\beta e^{-\beta(m-m_0)}}{1 - e^{-\beta(m_p - m_0)}} & \text{for } m \leq m_p \\ 0 & \text{for } m > m_p \end{cases}$$

CUMULATIVE FREQUENCY:

$$F = \frac{e^{-\beta(m-m_0)} - e^{-\beta(m_p - m_0)}}{1 - e^{-\beta(m_p - m_0)}}$$

Where m is the magnitude

m_p is the maximum magnitude

m_0 is the smallest magnitude of interest

Beta (β) may be calculated where the "b-factor" has been empirically determined by:

$$\beta = -2.3025 b$$

FREQUENCY

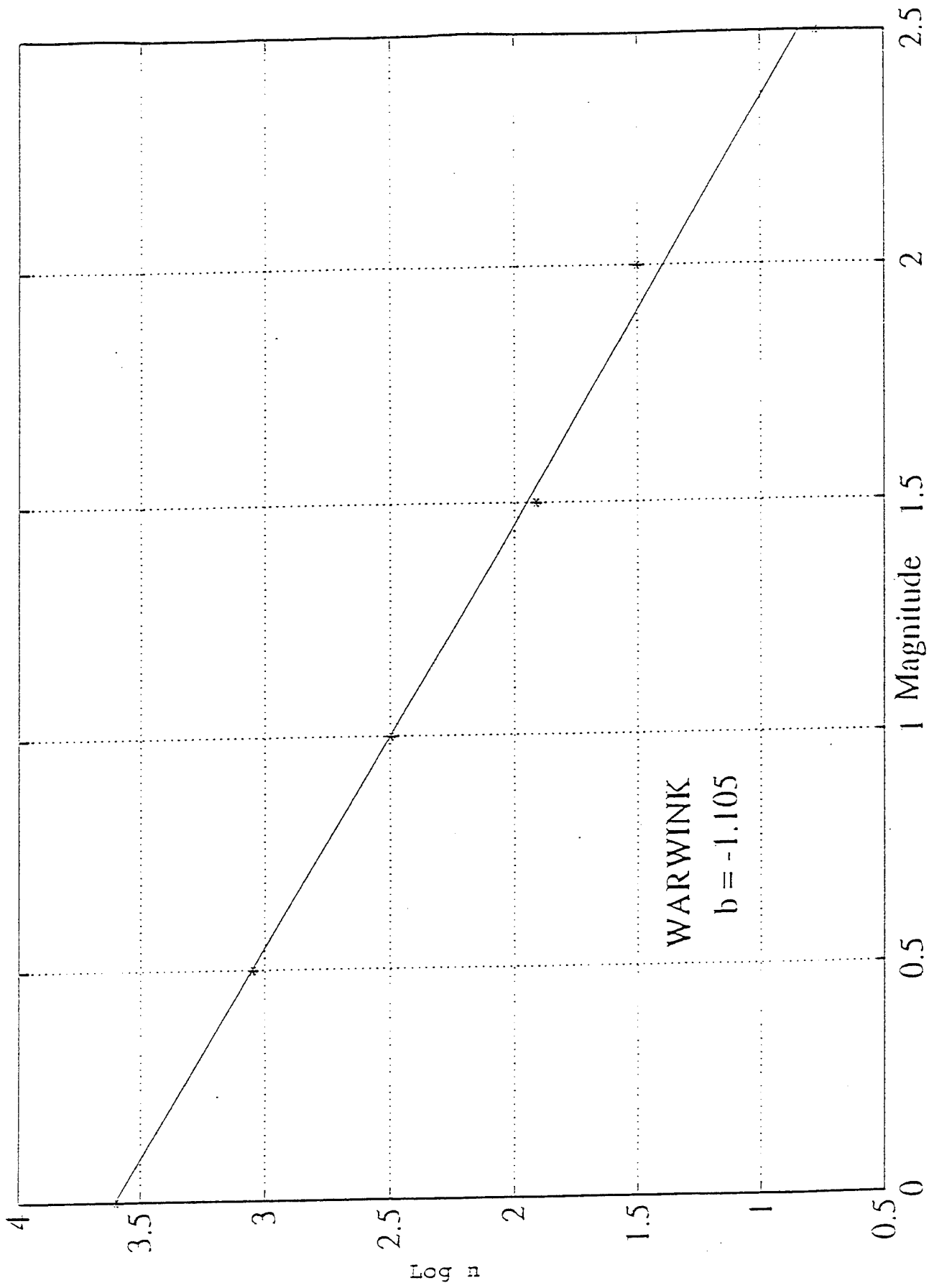


Figure A2. -- Magnitude regression curve from histogram of War Wink field, Texas.

These distributions were, to my knowledge, first used by Consentino et al. (1977).

Based on the estimated b-factor, Figure A3 shows a cumulative distribution of magnitudes at War Wink that closely fits the observations. Using an appropriate moment-magnitude for the region, Figure A4 shows the cumulative moment distribution. Conservation of energy requires that as the magnitude decreases, the cumulative moment should be bounded.

Writing the Gutenberg relation

$$\log N = a + b m$$

and the moment-magnitude relation

$$\log M_0 = d + c m,$$

assuming a Brune source model, and following Aki (1981) the fractal dimension is given by

$$D = 3 \frac{|b|}{c}.$$

The cumulative moment will be bounded for decreasing magnitude if $|b| < c$, which implies that the fractal dimension must be less than 3, a physically reasonable result. The fractal dimension for the War Wink field is 2.2. Figure A3 shows that War Wink does not pose a significant problem for the seismic monitoring system, because only a few events per decade are expected to exceed magnitude 2.5.

The Rangely oil field in Colorado has been studied in sufficient detail to allow a similar analysis (Gibbs et al., 1973). Histograms based on 976 events over a 7 year period were used to provide the data for Figure A5, from which the b-factor was determined. The cumulative distribution is shown in Figure A6 and the cumulative moment distribution in Figure A7. Again, the cumulative moment is bounded for decreasing magnitude. The fractal dimension for the Rangely field is 1.8.

Figure A6 shows that Rangely is not a serious problem for the monitoring system in that only a few events larger than magnitude 2.5 are expected each year - magnitudes larger than 3 are rare. But the Rangely field differs from War Wink in one important aspect. Whereas seismicity at War Wink is

NUMBER OF EVENTS GREATER THAN M PER YEAR

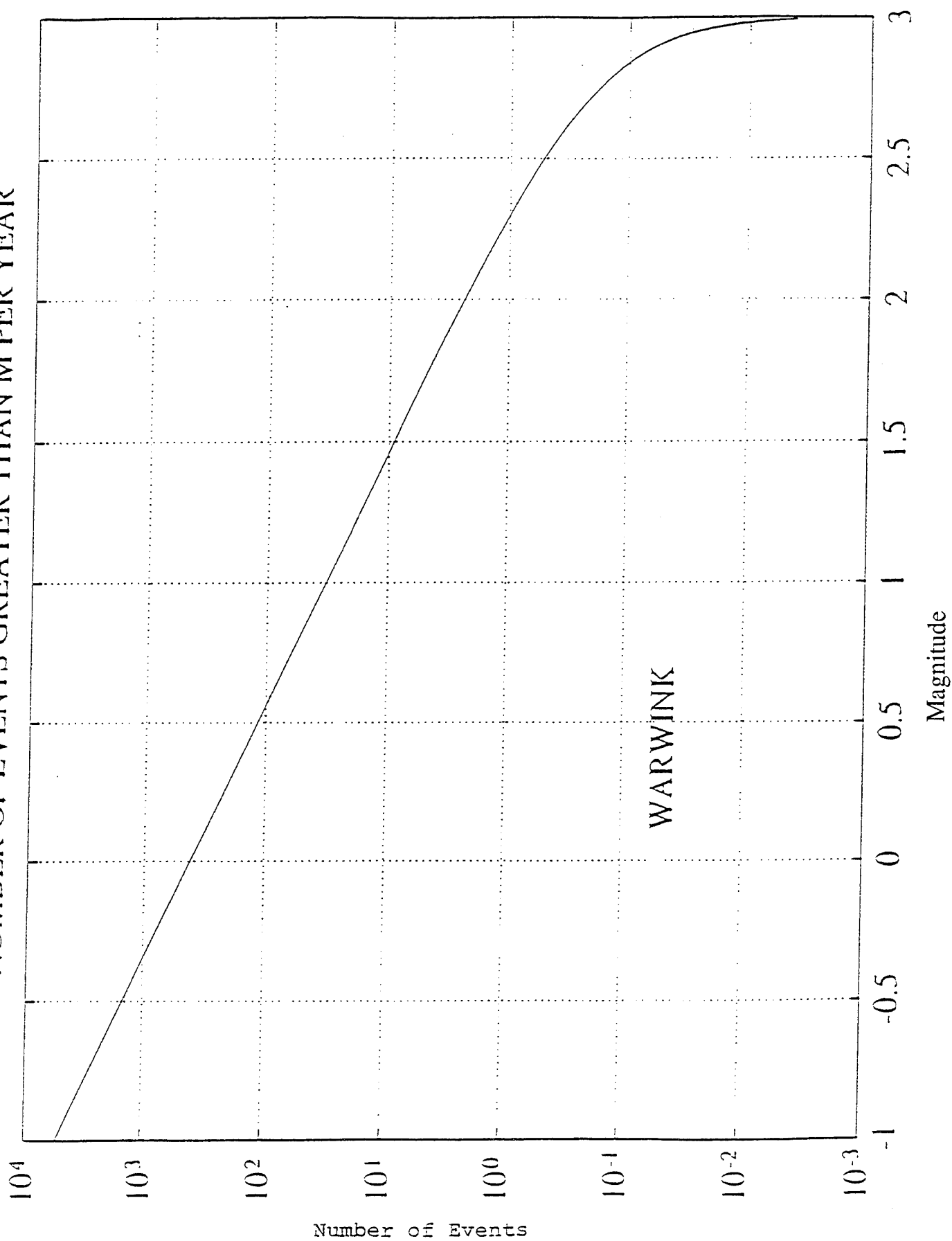


Figure A3.-- Cumulative distribution of magnitudes of War Wink field.

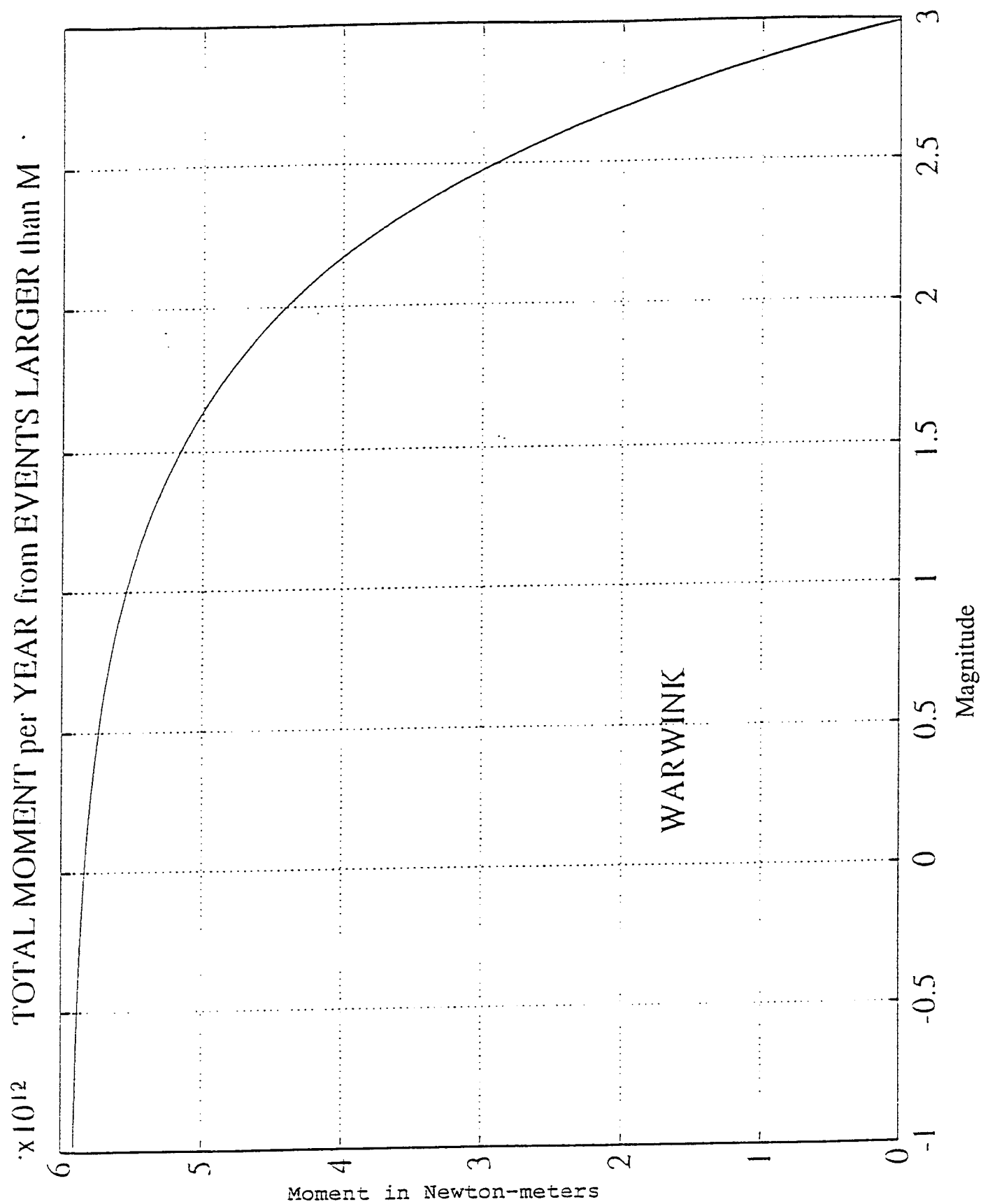


Figure A4. -- Cumulative moment distribution for War Wink field.

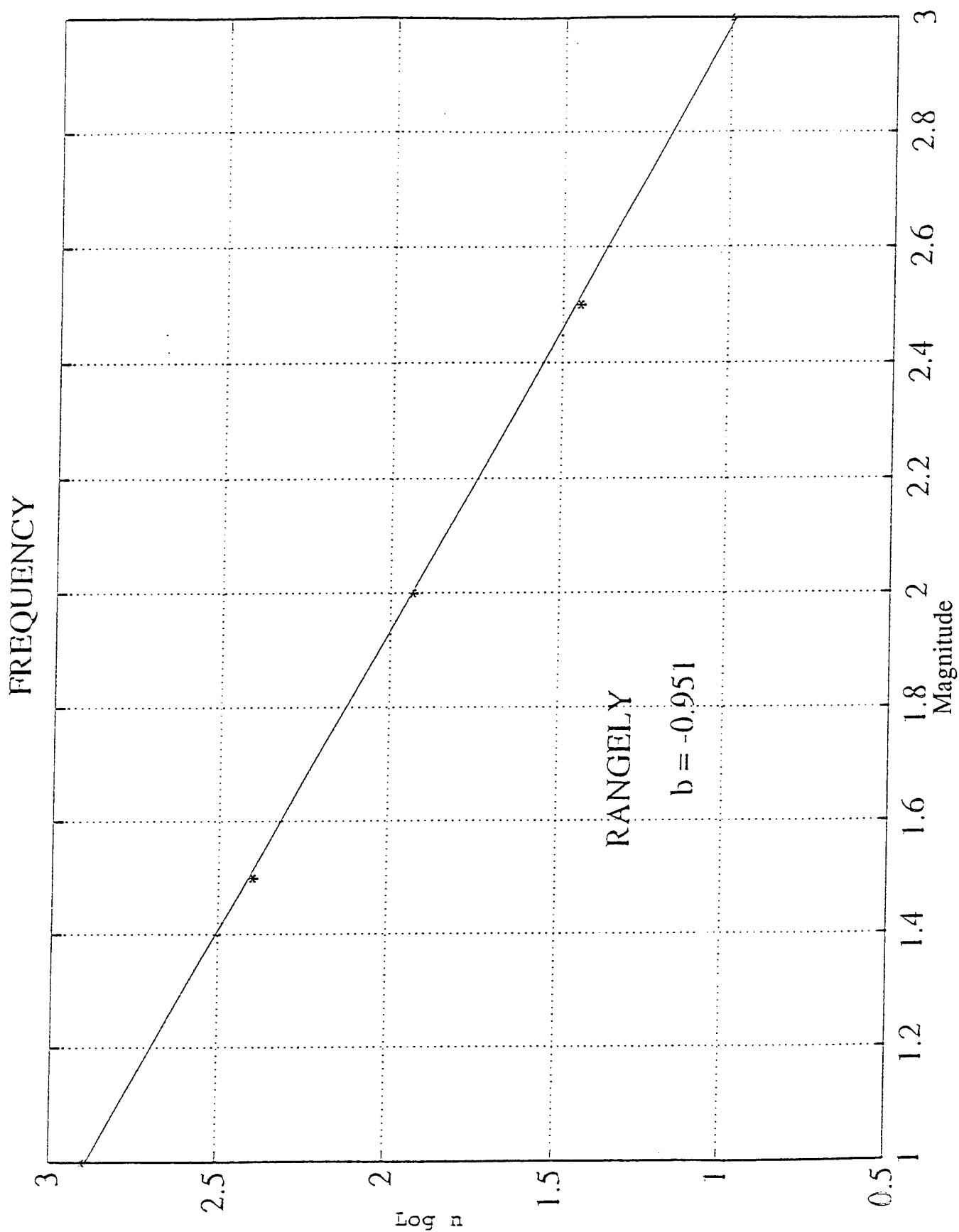


Figure A5. -- Regression curve from histogram for Rangely field, Colorado.

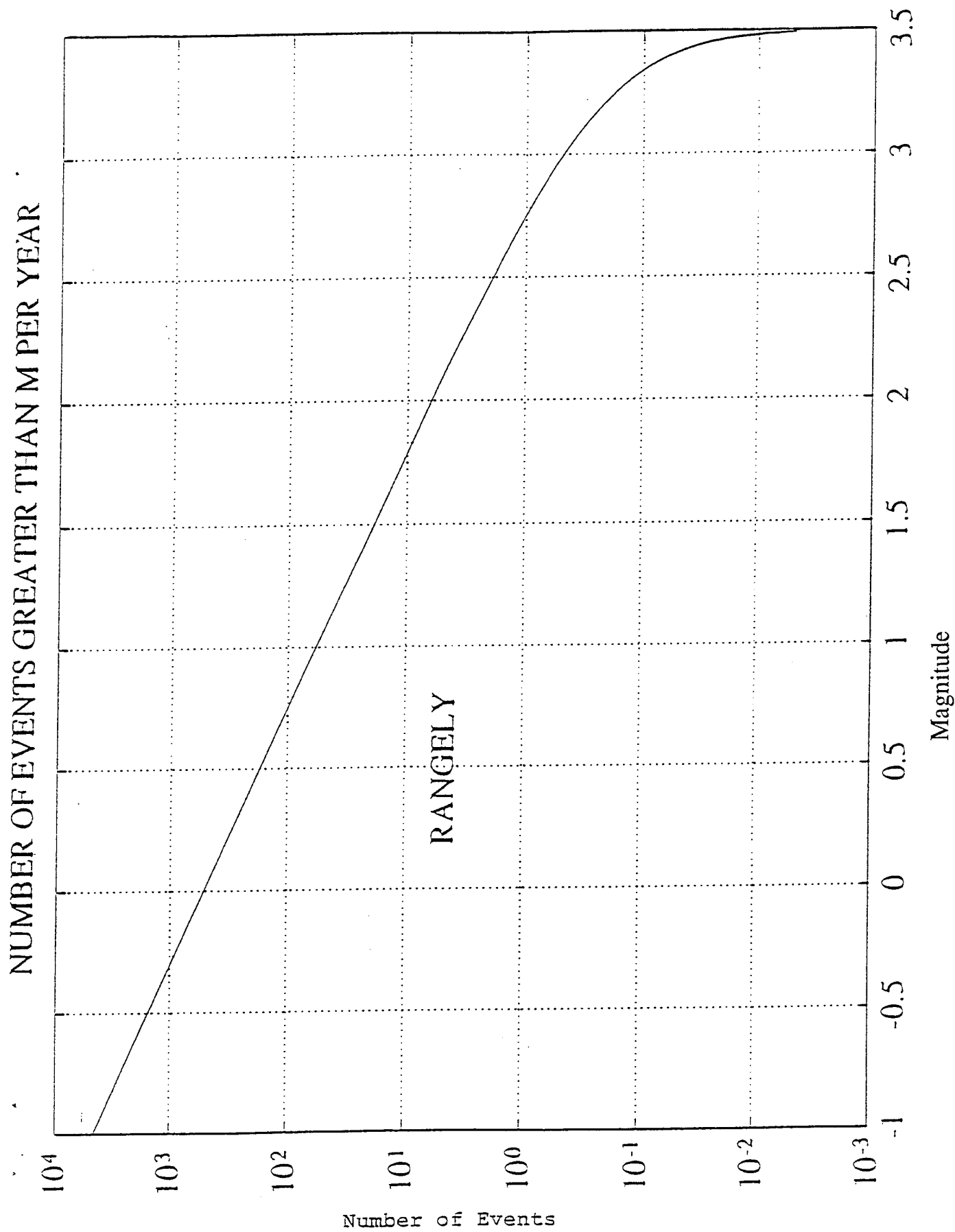


Figure A6. -- Number of events greater than M per year for Rangely field

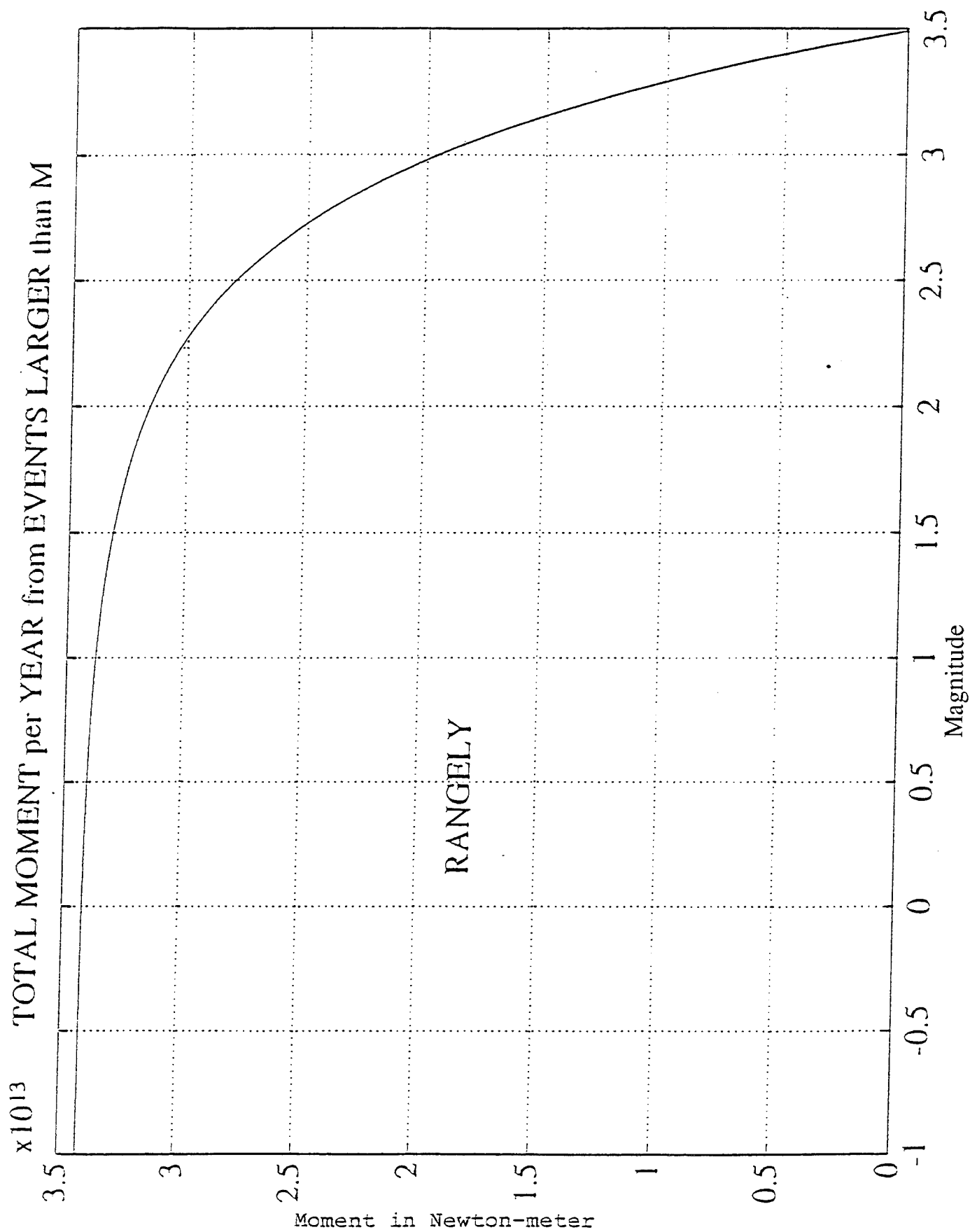


Figure A7. -- Total moment per year from events larger than M for Rangely field.

induced by gas production as at Lacq, seismicity at Rangely is induced by the injection of water as part of the petroleum production process. Raleigh et al, (1976) showed that the level of induced seismicity could be significantly increased by increasing the water injection pressure and volume.

By far the largest induced events are associated with oil fields undergoing water injection. The largest reported to date was mb 5 in the Cogdell field in the northern part of the Permian Basin. The data needed to analyze the seismicity of the fields producing the largest earthquakes, as was done for War Wink and Rangely, are not available.

Seismically active oil and gas fields are known to exist in the Middle East and Central Asia, but have not been studied in detail. Many of the producing regions (Permian Basin, Iran, Iraq) have thick, underground salt deposits suitable for the construction of decoupling cavities. Do these fields provide a significant problem for a CTBT monitoring system? Clearly their induced seismicity will add to the analysts' burden, but does the opportunity exist for controlling the seismicity in order to mask a decoupled explosion? These questions cannot be answered based on currently available data.

CONCLUSIONS

The threat of evasion of a CTBT by cavity decoupling of a 1 to 2 kt device drives the seismic monitoring threshold down to m_b 2.5. The problem of finding a decoupled explosion in the 100,000 events per year that will be detected by the ISMS is formidable, and, after detection, we have no proven technique for distinguishing a decoupled explosion from a tamped explosion of comparable magnitude short of on-site inspection. If a suspect event occurred in a seismically active oil field, OSI would be faced with a paradoxical problem. Whereas a tamped explosion would be expected to produce very small aftershocks, a decoupled explosion would not. An active field such as Rangely is expected to produce several events per day of magnitude zero or greater at all times. OSI will surely find events, but they need not be aftershocks. The possibility of cavity decoupling masked by industrial explosions or by seismicity induced by mining or hydrocarbon production constitutes the greatest threat to the success of a CTBT monitoring strategy.

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APPENDIX B. -- THE ARPA MODEL 94 REGIONAL ARRAY CONCEPT

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Since the first Group of Scientific Experts Technical Test (GSETT) in 1984, Southern Methodist University (SMU) and Science Horizons Incorporated (SHI) have been involved in the development of seismic data acquisition systems to improve the capabilities for detection, location and identification of seismic activity around the globe. SMU and SHI cooperation from 1988 to 1991 during GSETT2 included designing, installing and operating the U.S. GSE seismic network consisting of six three-component seismic stations distributed around the country. Our cooperative efforts have resulted in the design and implementation of the prototype ARPA Model 94 array at Lajitas. The Lajitas array consists of eight vertical seismometer sites and one three component broadband site, configured as one central location and two 'rings.' The central location is the three component broadband site, the inner 'ring' contains three vertical systems at a radius of approximately 0.5 km and the outer 'ring' contains five vertical systems at a radius of approximately 2.0 km.

As an integral part of future GSETT experiments, which call for a network of approximately 50 'Alpha' arrays, the Model 94 array has been designed to provide the highest quality data at a minimum cost. At the central element of the array we have installed a prototype Geotech Instruments KS54000 posthole seismometer. This seismometer is a three-component, broadband sensor comparable to the KS36000 borehole sensors used worldwide by AFTAC to record long-period seismic data. The major difference with the posthole version is that it is installed in a shallow cased borehole and is packed in sand. This procedure requires no special installation equipment, no downhole remote leveling and locking electronics, and eliminates the need for a hole-lock mechanism that is suspected of causing excessive 'noise.' Our initial comparisons between the posthole KS54000 and the AFTAC standard KS36000 collocated in a 100-meter borehole at Lajitas indicate that the

performance of the posthole version meets or exceeds that of the borehole instrument. A three channel SHI AIM24 digitizer collects the data, time tags each sample with time from a GPS receiver and communicates with the array hub by a digital radio link. The AIM24 digitizers provide between 20 and 21 bits of resolution, approximately 120 db of linear dynamic range, making gain ranging unnecessary. The GPS receivers provide timing accuracy to within 10 microseconds of world time (UTC). The digital radio modems communicate at a rate of 9600 baud. The use of data compression and error-correcting communication protocol assures a minimum of data loss. A status log keeps track of all errors and message traffic between the AIM, GPS receiver and array hub. All other array elements consist of Geotech Instruments GS-13 vertical seismometers and low-noise preamplifiers. The seismometers are installed at the bottom of a cased borehole approximately 6 meters deep and all the electronics are mounted on rubber carrier strips that are suspended down the borehole to reduce the diurnal temperature fluctuations that can effect their performance. A SHI single channel AIM24 is used, as well as a GPS receiver, and digital radio modem identical to the central element. Each site is powered by a solar power array and deep-cycle batteries. The solar array produces a maximum of 128 watts at 17 volts which is regulated to 13.5 volts by a charge regulator that controls the charge rate of two 6 volt, 220 ampere hour deep-cycle, golf-cart batteries, wired in series to provide 12 volts. Total average power consumption at each element is slightly less than 12 watts. Figure B1 shows the electronics, mounted on a carrier strip ready for installation in the borehole. In Figure B2, the photo on the left shows a completed element of the array including the borehole mounted NEMA enclosure, solar array, GPS receiver, and radio antenna; the photo on the right shows the interior of the NEMA enclosure containing the deep-cycle batteries.

The use of modern seismic data acquisition equipment in boreholes, implementation of the Global Positioning System (GPS), solar power arrays at each site and the incorporation of radio frequency digital modems allowed us to minimize the construction requirements of the array. Figure B3 shows the array layout on a topographic map of the area. The topography shows deep arroyos and a series of horsts and grabens that would have made conventional, hard-wire trenching methods impossible. Siting of future arrays based on the ARPA Model 94 design will be much easier because of the



Figure B1. -- All of the electronics for one site are shown mounted on the carrier strip, ready for installation in the borehole.

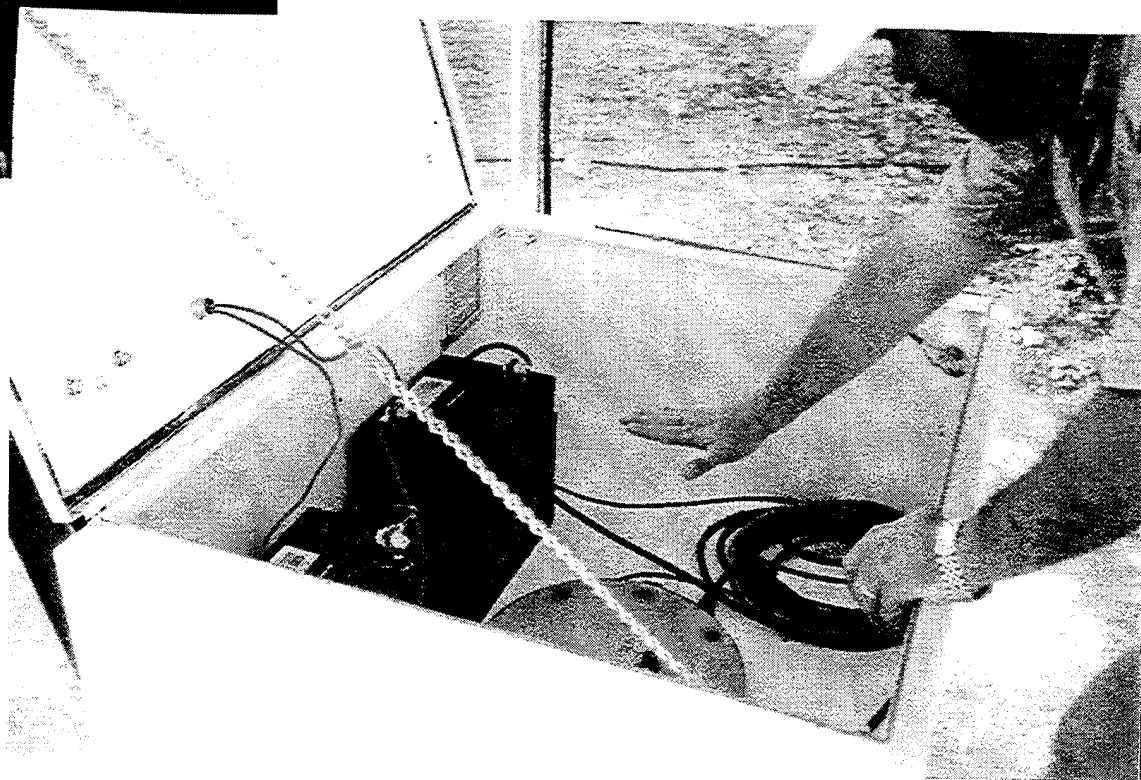
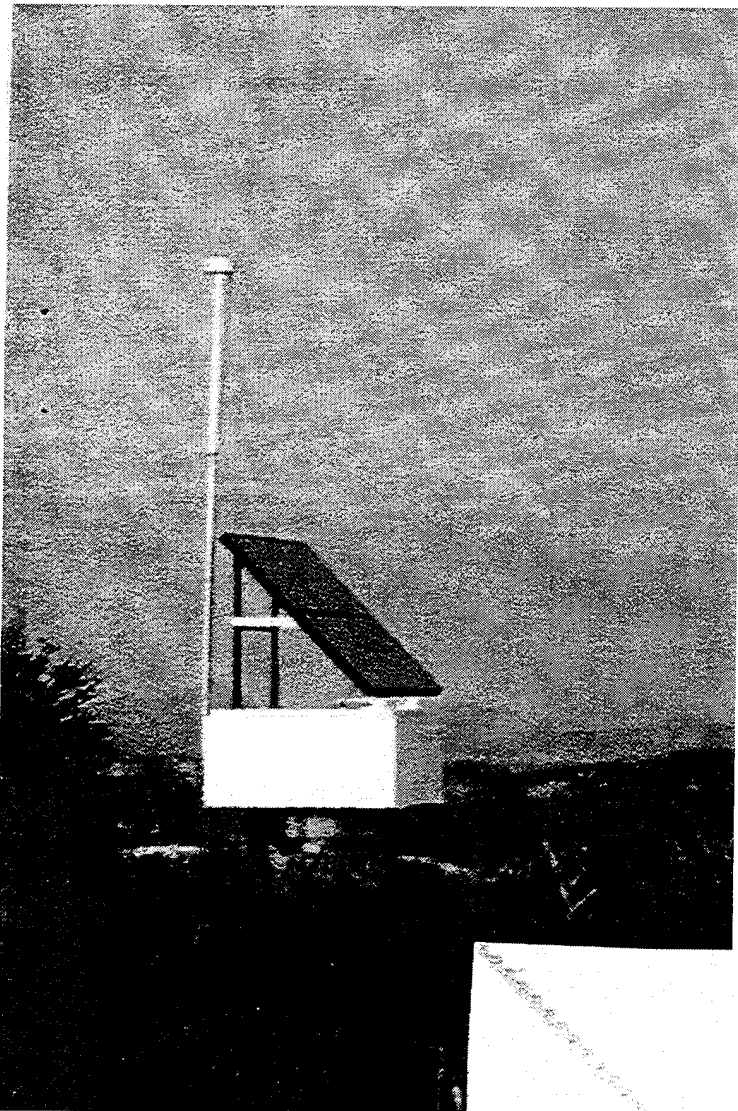


Figure B2. -- Photo on left shows a completed element of the ARPA Model 94 array near Lajitas, TX. On the right is a photo showing the inside of the MEMA enclosure containing the deep-cycle batteries.

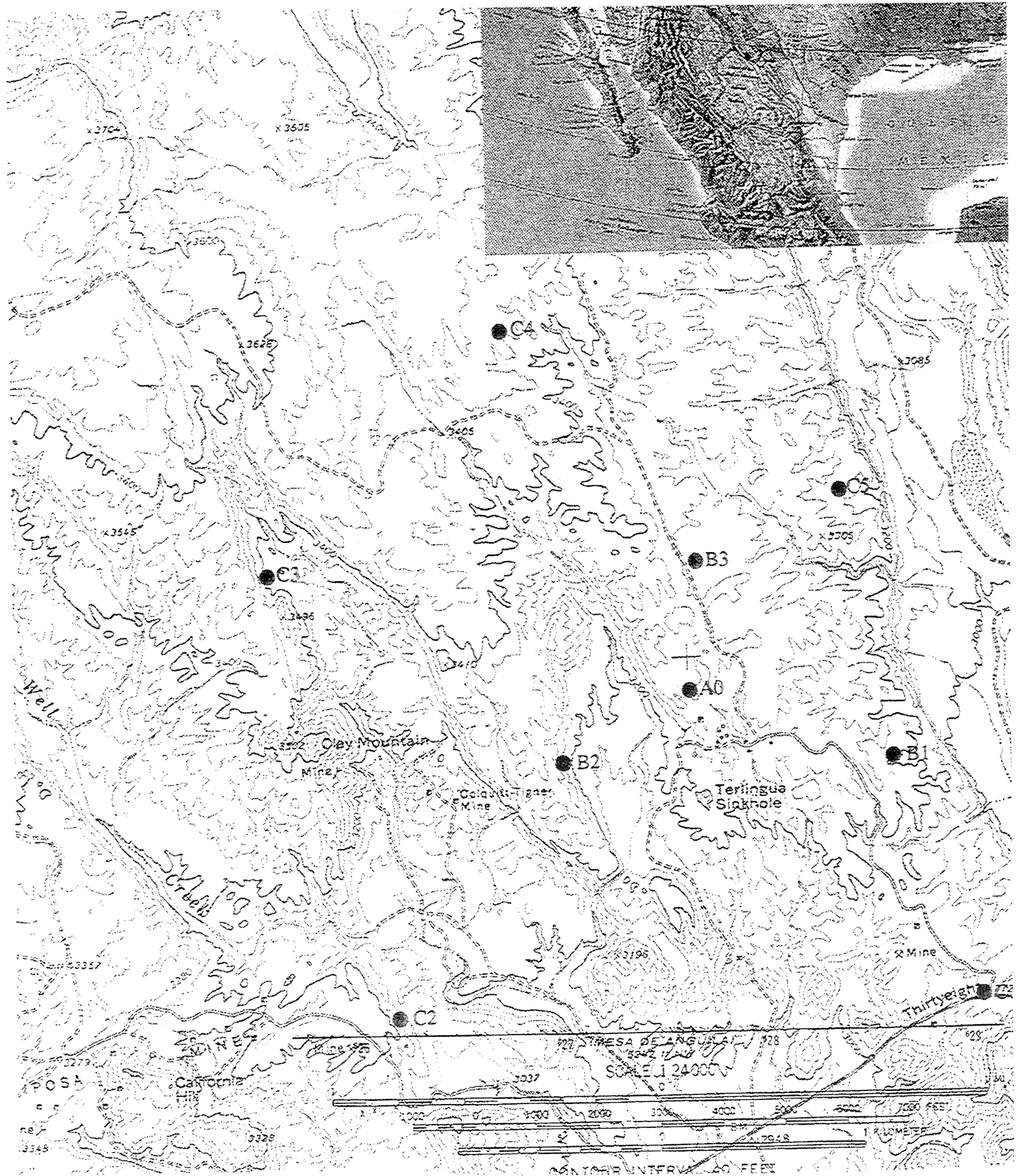


Figure B3. -- Topographic map of the area and layout of the ARPA Model 94 array at Lajitas.

flexibility and modularity of the system. In addition, the modular nature of the system makes it possible to move elements to improve the array response and to add non-seismic sensors at a reasonable cost. We are currently considering the use of the prototype array to detect infrasonic acoustic signals by incorporating broadband microphone data with the seismic data at array elements. This research may lead to detecting and recording infrasonic acoustic data with the seismometers already in place at each Alpha array.

In addition to providing the array systems, we have developed new data processing techniques that minimize errors in estimated azimuths and distances to regional events. This time-domain processing technique, using a cross correlation algorithm, has the capability to determine azimuths with standard deviations of less than 1.5 degrees. Figure 4 shows the results of processing one event with an estimated azimuth having a standard deviation of 1.4 degrees. Our experience in GSETT-2 revealed that three-component station azimuth estimates had a precision of ± 10 to 15 degrees, which was very dependent on signal to noise ratios. Figure 5 is a map showing the location of all regional events located during the six weeks of GSETT-2. Each of the events had to be large enough so that an analyst could identify at least two seismic phases (Pn and Lg normally) and compute a back azimuth estimate using three component data. The map clearly shows 10 to 15 degree azimuth errors for numerous events known to be mining explosions in a small area of southwest New Mexico. At a distance of 500 km, these uncertainties in azimuth imply a location error of about ± 100 km for the 3-component station, while the array precision results in an uncertainty of less than ± 13 km. This represents an order of magnitude improvement in location precision when using the ARPA Model 94 array and our processing techniques as compared to standard three-component processing. For the above reasons, we think the ARPA Model 94 array design is a very cost effective method for obtaining data to be used in the automated system needed to locate and classify seismic events.

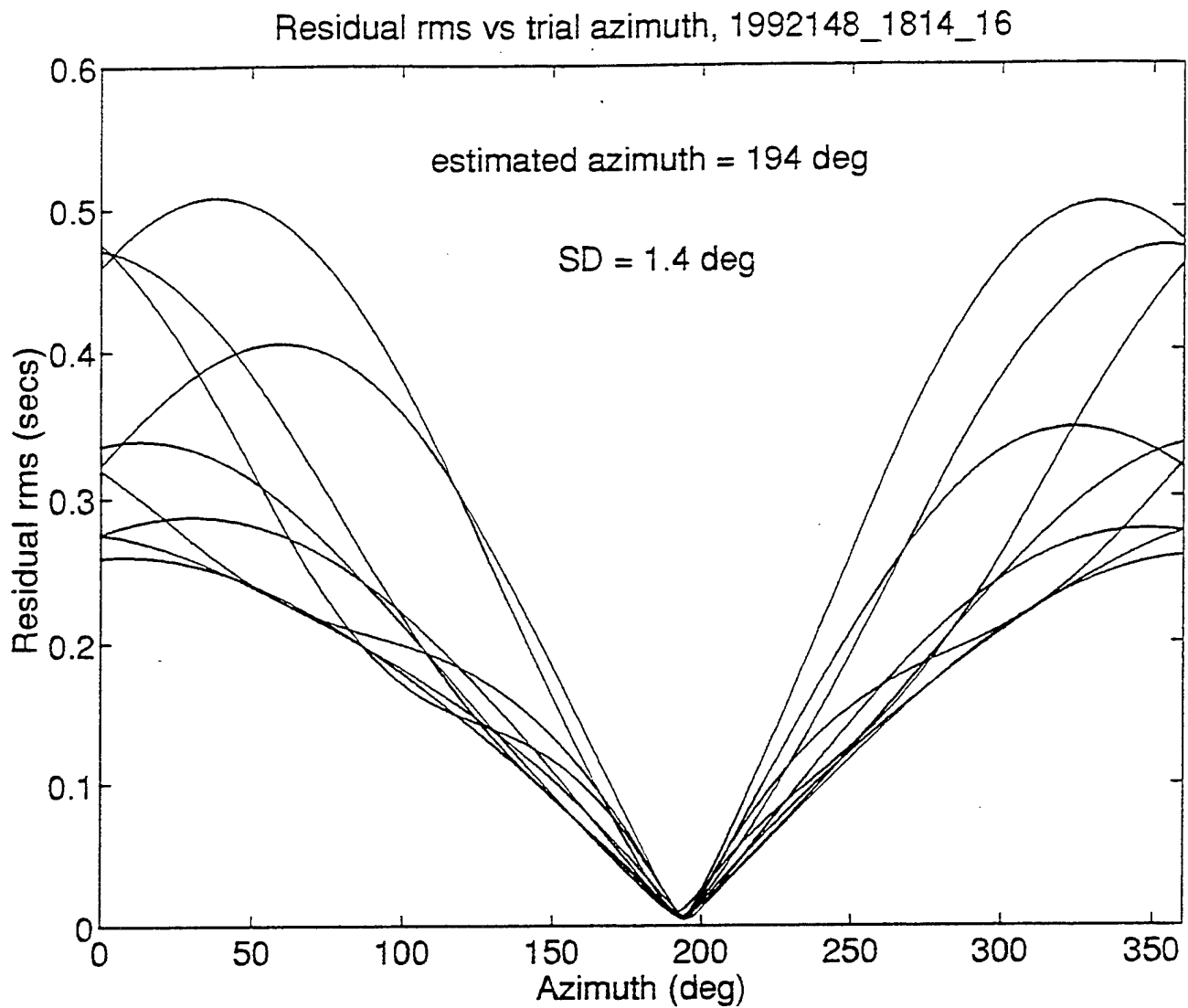


Figure B4. -- Time-domain processing using a cross-correlation technique can determine azimuths from the ARPA Model 94 array data with a standard deviation of less than 1.5 degrees.

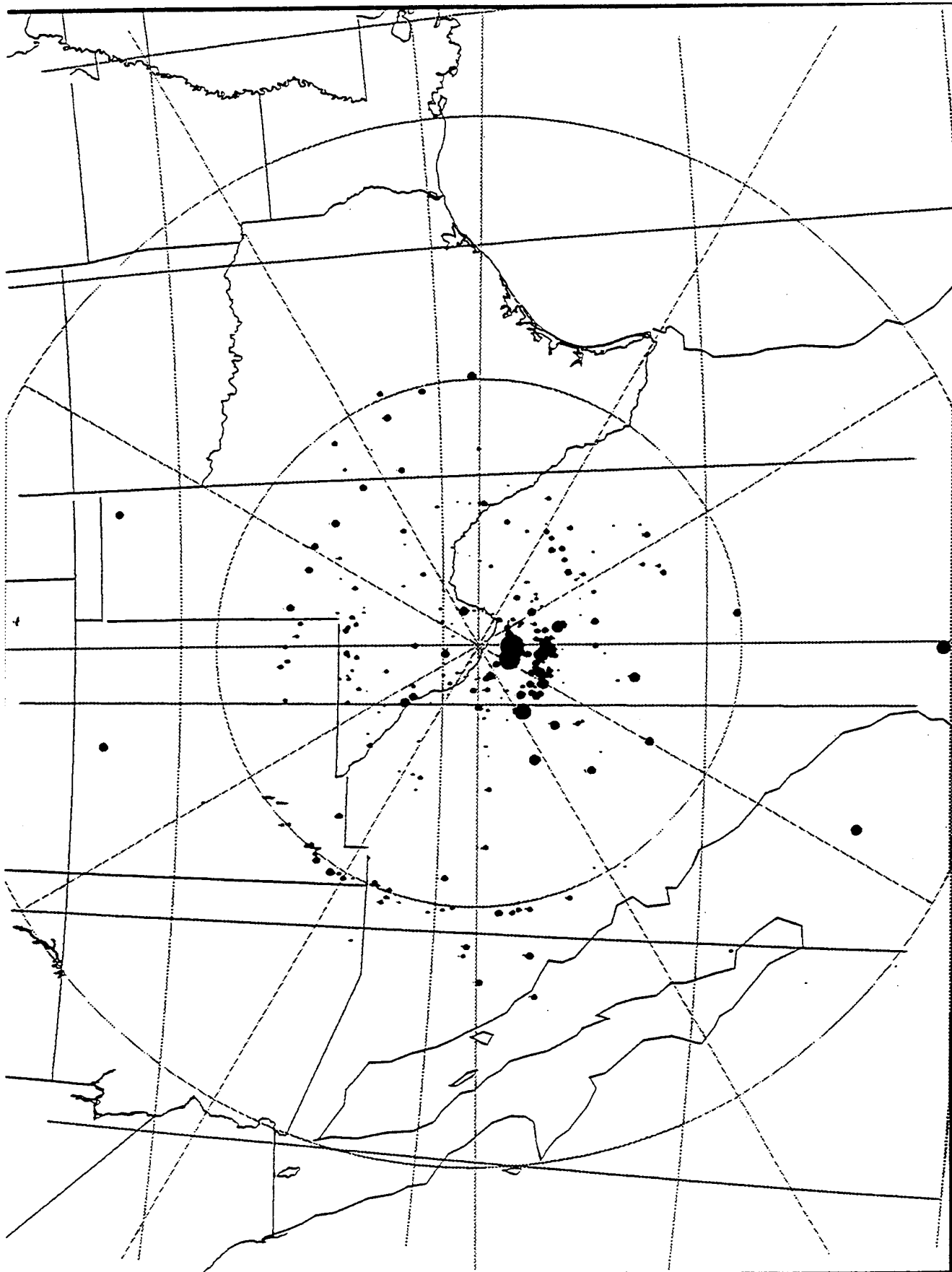


Figure B5. -- Locations of GSETT-2 regional events determined using three-component, polarity-analysis techniques.

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